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Flight Control Design Best Practices Relative to Active Control Technology

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Task Group SCI-26 was formally initiated in 1996, in response to well-publicized and highly visible accidents that had occurred in the latest technology aircraft both in the US and in Europe. These accidents were due to deficiencies in the flight control system designs. Other recent programs had less-well-publicized FCS development problems, with time and cost overruns more the rule than the exception. The Task Group has just published a report, which begins with a review of some examples of flight control problems. They span the history of flight from the time when the practice of flying was preceding theoretical developments up to more recent time when it might be thought that flight control designers "should know better". Then there is a chapter detailing lessons learned from various programs with positive results, which leads into a section detailing a series of recommended best practices. The second part of the report continues with some theoretical aspects. First, there is a discussion of flying qualities criteria, and the current state of the art of "carefree handling" which is related to this symposium. Next there is an extensive discussion of the latest results from research into PIOs, followed by a discussion of modelling and system identification. The Task Group members originally laid out this report to present an assessment of design methods, but no correlation was found between the method used and the problems of the past, or the successes.

The theme of the symposium, "Active Control Technology", is interpreted to mean the use of flight control technology to minimize the pilot's workload in accomplishing every mission task. Specifically, it covers a range of applications from tailoring the responses to prevent undesirable characteristics, such as departures or limit exceedances, all the way through to automatic recovery systems that take control away from the pilot. The objective of this paper is to summarize the Task Group results with particular emphasis on best design practices to achieve the optimum benefits from active control technology (ACT).

Introduction

Flight control design technology has evolved along with the development of the airplane itself. As flight envelopes expanded and mission tasks became more complex, flight control design became more sophisticated. Active control technology, by definition, means the tailoring of aircraft response to inputs beyond the basic pilot control and maneuvering. Even mechanical systems in recent aircraft were designed with scheduling to limit pilot inputs in certain conditions, e.g. to minimize susceptibility to departure. One example is to reduce the pilot roll command gain at higher angles of attack in order to prevent departure. The trend towards fly-by-wire technology has given designers even more flexibility in the application of ACT. Another example would be to prevent the pilot pitch commands from causing the aircraft to exceed a certain load factor. These effects can be achieved by tailoring the responses to the pilot commands so that they still appear natural, referred to as ACT1 for this discussion. At the extreme, however, is the application of systems such as Automatic Ground Collision Avoidance, where control is taken away from the pilot completely, ACT2 when there is any distinction to be made. In all cases we can consider that ACT is an extension of basic flight control design and should be integrated as much as possible.

The previous RTO symposium on ACT was in 1994, "Active Control Technology: Applications and Lessons Learned", AGARD-CP-560. The Technical Evaluator stated: "An AGARD Working Group might be the proper means to consolidate valuable insights gained during recent demonstrator and prototype projects ....". A Working Group was formed and has just completed a technical report which is in publication, Reference 1. As stated in the report, problems have occurred from the very beginning of flight up to the present time where it might be thought that "designers should know better". Also, FCS problems are not unique to digital systems, there have been problems with every form of FCS. There are, however, unique aspects of fly-by-wire (FBW) control systems. The most obvious, and frequently the most important, is that there is no direct connection between the pilot and the control surfaces. Since an extreme application of ACT is to take control away from the pilot, special attention is required to provide appropriate connectivity through the design of the FBW system. In

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addition, the very flexibility of the digital technology has also given designers more flexibility for error in new ways. Reference 1 contains recommended Best Practices for FCS design. The object of this paper is to discuss each of the recommendations from that report in the context of applying ACT to a system design. It can also be admitted that some points are made repeatedly for additional emphasis.

Background

For the purposes of this discussion, we can assume that artificial stabilization is common. The focus of Active Control Technology is the extension of flight control design beyond stabilization and control. The term "carefree handling" is typically used to designate the design of the control laws to prevent pilot inputs that would cause departures, exceeding limit loads, etc. Then we can consider a progression to recovery directions for the pilot to follow, through to complete intervention of the control system.

The initial elements of ACT can be considered to be in systems like stick pushers as an indication of approach to stall. The later aircraft with mechanical control systems, such as the F-15, included ACT in the form of command gain reduction to minimize departure susceptibility. Fly-by-wire technology has given designers even more freedom to develop the technology. In Reference 1, the application of "carefree" handling to two aircraft with different technology status is discussed. An existing aircraft can be upgraded during its lifetime with the new technology development. There is also discussion of what is possible today for a combat aircraft of the newest generation. The principle is the same for both, a reliable control system with a good sensor system for measuring the flight condition enables the implementation of "carefree handling". The primary difference is whether the functions are added to an existing control system, or can be integrated into a new design from the start.

Also as discussed in Reference 1, a Pilot Activated Recovery System has been shown to be effective. This system was pilot selected and provided guidance which mimicked the recovery procedures that are taught to the pilots. It was very acceptable to the pilots, since it only provided guidance as an aid to manual control.

The above approaches are oriented towards helping the pilot to the maximum extent. There still exist possibilities where the pilot does not realize the situation or is temporarily incapacitated. In addition, there have been many accidents where warnings were not sufficient. A human pilot in a stressful situation will ignore everything except a primary focus which may not be the correct one. This leads to consideration of fully automatic systems to take over control. The flight test results from an Auto Ground Collision Avoidance System program show the benefits of an automated system (see References 2 - 4). It shows that nuisance warnings are almost zero and that interference with the pilot is basically non-existent. Pilot acceptance of automated systems has been a problem in the past. This reluctance was based on insufficient knowledge of automated system operation or experience with inadequate manual systems. Future aircraft will be more complex both in pilot workload and in display technology. These facts alone will make the need for more automation imperative. An automatic GCAS has the advantage over a manual GCAS in that it does not have to compensate for the pilot's reaction time. This fact alone should eliminate most nuisance activation. There are still database errors that can cause nuisance cases. As the database gets more accurate over time, these also will be eliminated.

All the design aspects of ACT and carefree handling are subject to the Best Practices discussed later. An early program decision is mandatory to define the extent of the technology. It does increase the design effort and therefore must be justified. Even in the simulation and especially in flight test a higher effort is needed to clear the aircraft for "carefree" maneuvering. Nevertheless the advantages are so big that it should be considered for every modern combat aircraft. In addition, many aspects could transition into commercial and military transport aircraft. The problem may be cost, unless it can be justified on the basis of improved safety.

The Design Process

The flight control system design process is expressed in graphical form in Figure 1.

This figure can be interpreted to apply to both an upgrade and a new design. It shows a logical process, starting with consideration of the various requirements, to establish a well-defined set of FCS design criteria. This is the time when the application and extent of ACT should be defined. The best results will be achieved if ACT is included in the design requirements and the design process as early as possible. It is essential that the whole team understands these requirements. These allow definition of the control law architecture and an initial design to be established. This is also the point at which consideration of non-linearities should start, such as those associated with actuation system specifications, aerodynamic characteristics, etc.

Some aspects of ACT can be included in the initial design requirements, such as load factor protection. Others may need to be considered as a response to problems that are encountered in flight test. It is quite common in the later stages of FCS verification and validation to perform sensitivity analyses accounting for uncertainties in the aerodynamic model used in the design process. These analyses are intended to ensure system stability for a certain

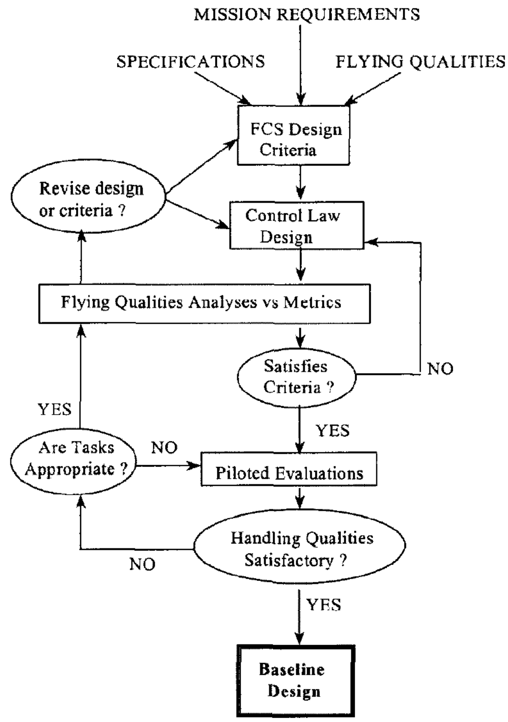

Figure 1. Flight Control System Design Process

percentage variation in aerodynamic derivatives. It may also be worth doing "what if" exercises to discuss potential approaches if there is some variation beyond these values. What if lateral/directional coupling is significantly different from predictions. Is there a feedback or command path that would be required that is not in the basic control laws? One may decide that it is prudent to include such a path with zero initial gain as cheap insurance.

After the design requirements are defined and agreed, there is then a loop of analyses to ensure that the control law design meets the criteria that were established. These analyses should be a package of methods that are complementary, documented and can initially be informal, but must be thorough. The recommended approach to achieving satisfactory flying qualities is to assess the predicted responses to cover all flight conditions, including all non-linearities and pilot input amplitudes. This becomes especially important if we are considering ACT as protection at the extremes of the flight envelope. One critical aspect of the process follows the assessment in piloted simulation, any deficiencies must be corrected by analysis.

Design Best Practices

The design process should not be considered as a rigid serial process, even though it is convenient to discuss it that way as in Figure 1. In fact, many parts are performed concurrently and/or in iterative loops but it is necessary to keep the total process in mind in order to maintain the appropriate connections between the various components. Similarly, the following Best Practices should be considered in total and not serially.

Establishing aerodynamic design and system performance requirements

Some of the difficulties associated with flight control laws design can be created very early in an aircraft's life-cycle by the design of the airframe and the related performance specifications used for its FCS hardware. It is important that the control law designer is involved in the definition of the aerodynamic characteristics and the associated FCS equipment performance, at an early stage. He or she should also be involved in aspects of the wind tunnel testing as the user of those characteristics. If these are not satisfactory, he may be tasked with compensating for undesirable physical behavior by including appropriate functionality within the flight control algorithms. Whilst it is accepted practice to provide artificial stabilization, there are bounds on what can be safely achieved, simply due to the laws of physics. Even before the physical limit is reached, the financial cost of providing artificial stability may be very high, owing to the required performance of the FCS hardware.

There are specific recommended best practices addressing sizing and placement of control surfaces, specification of data sensors and actuation system characteristics. These areas are particularly susceptible to being frozen early in the design process.

It is tempting to avoid analysis of non-linearities in the early stages, because they would mainly be engineering judgement. The real problem occurs if early decisions are made without any analysis and data. There is always resistance to changes, which only increases through the stages of the design process. For some aspects of ACT, differences from predicted characteristics are likely to occur in the later stages of flight testing because they are towards the flight envelope limits. At this point, it may be assumed that the characteristics are being identified with more certainty. It should be possible to accommodate differences up to some magnitude (within the range of sensitivity?) by gain changes. For larger differences, the really good design team would have it covered through the "what if" exercises discussed above !!

Modelling and analysis of the unaugmented vehicle

Before beginning any control law design, it is important to study and fully understand the dynamics and the non-linearities of the unaugmented vehicle, including those of the FCS hardware. This analysis will include the traditional aspects, such as actuators, the air data system, etc., but should include everything affecting the control system, such as the powerplant. It is also important to understand how these are likely to affect the aircraft's control characteristics as its operating condition varies. If this is not done then there are likely to be some surprises later in the design process, which will require re-work, i.e. overruns in time and money.

This is where considerations that were used in the aerodynamic design can be integrated into the modelling and analysis. An estimate of probable nonlinear aspects should be included. It is also wise to consider the probable accuracy of the predicted characteristics in order to define appropriate ranges for sensitivity analyses and "what if" exercises. Obviously, the decision on how ACT will be integrated into the FCS will have a large influence on the results.

Design criteria and flying qualities specifications

The two areas above are essential preparation for the FCS design, but the real critical point of the whole design process starts with definition of the design requirements. The biggest influence of ACT, and also the most critical, is in this definition of design criteria. The design team (which is discussed further as a management practice) needs to agree on the criteria. Many aspects of ACT are not covered explicitly in military specifications, therefore, a clear agreement on the intent and the extent needs to be documented at this point. The requirements will also vary significantly depending on the class of aircraft being considered and its mission.

The military flying qualities specifications may have been misused as often as they have been used correctly. A very common statement is that they apply only to the linear small-amplitude responses. The US military specifications have never stated this, they actually defined flight envelopes over which the required criteria were to apply. Because of the practical problem of the unavailability of non-linear theories, the non-linear effects have frequently been neglected, or even ignored, in the past.

The introduction of Equivalent Systems into MIL-F-8785C (Reference 5) provided a means to characterize the actual aircraft response, whether it was linear or non-linear. There was an explicit requirement stated in the specification that ALL non-linearities were to be included in the equivalent system. The characterization was in terms of a conventional linear response model, and was therefore, mathematically not exact. Such an approach would be a better start than nothing. Since the introduction of MIL-F-8785C, other methodologies have been developed which apply equally to non-linear responses as well as the linear, e.g. Reference 6. The problem will be how to produce credible models, especially the nonlinearities

Many aspects of ACT, especially protection against violating limits of the flight envelope, should be expected to require consideration of non-linearities. One example is the protection against departure as angle of attack increases into a range that may trigger uncontrollable yaw if the pilot commands too high a roll rate. The solution is typically a non-linear command gain as the aerodynamic characteristics are becoming more and more non-linear. This non-linearity is straightforward and relatively benign. At the other extreme may be the requirement to consider actuation deflection, rate and acceleration limits as part of the recovery control laws. The recommended approach is to include a spectrum of nonlinearities, even based on judgement until more refined models can be developed.

The recommended Best Practice to define the system flying qualities requirements would be to extend the military specification criteria rather than just discard them. The first question would be whether the mission required the system to limit responses to stay within a conventional envelope or provide satisfactory flying qualities in an extended envelope. As an example, the Permissible Flight Envelope can be defined to extend to any angle of attack. A first estimate of required characteristics throughout this envelope, including recovery into the conventional envelope, should be the starting point. They can then be augmented with automatic functions and a definition of the extent of intervention into the pilot control.

Control law design and development

In a classical design sense, having established the capability to produce linearized models of the aircraft, its powerplant and FCS hardware, a grid of design points are selected to cover the required flight envelope. A series of localized controllers are then designed and implemented using gain schedules to cover the flight envelope. At this stage, additional non-linear functionality is added, for example rate limiting functions and authority limits. There then follows a comprehensive assessment of the design, leading through to flight clearance.

Reference 1 then continues with twenty Best Practices, the last of which concerns the design methodology. In the report it is stated that no correlation was found between FCS problems of the past and the methods used. There is also the promise that future developments of modern control, such as robust control theory, will change the emphasis of the given list of best practices. There should always, however, be the judgment and insight that comes from some application of a disciplined approach of designing to the agreed criteria. The physics of flight remain the same, irrespective of the design methodology.

When designing the control laws with ACT, at the lower levels, the pilot command inputs are reduced to avoid violation of all given stability and controllability margins and additional limitations (e.g. load factor). At the higher levels, the automatic system provides inputs that can change the pilot inputs dramatically. There is then always discussion as to whether the system is improving what the pilots think they can do. For the future, therefore, the "fuzzy logic" requirement for ACT is "to prevent all bad things from happening but the agility of the aircraft must not be reduced too much". This is a subjective evaluation when the pilots think that the control laws are preventing them from achieving some realizable performance objective. Part of the solution to this problem of acceptance is to design for minimum intervention, as discussed above in all three areas. Finally, it is mandatory that pilot selectable features should not be "dormant", i.e. it must be clear to every pilot exactly what the selected configuration is.

Control laws functional specification, implementation and verification

Whether the flight control laws are to be implemented in an analogue or, more usually these days, a digital flight control computer, some means of functional specification is needed to enable the laws to be implemented. For digital flight control, the functional specification will enable coding into the target machine's language and allow the implementation to be verified against the intentions of the designer. This, however, relates back to the previous Best Practice of thoroughly documenting "the intent of the designer". This does not change if the ACT aspects are an integral feature of the FCS, but 'add-on features' must follow the same rules.

Piloted simulation and handling qualities

It is common practice for the control laws to be thoroughly evaluated by piloted simulation. The initial task is to set up the control laws within the simulator's real-time environment and to establish the interface between the control laws and the pilot's controls and displays. The implementation must then be verified, prior to exposing the simulation to pilots. A series of piloted evaluations then takes place, during which the handling qualities and mission effectiveness of the augmented aircraft are assessed. This usually results in further developments of the control laws, as handling deficiencies are identified. It is critical, however, that this further development is done analytically.

A best practice is to plan for an integrated simulation program and ensure that all IPT members (especially pilots and managers) are clear that the various simulators are for evaluation purposes, to feed data back into the analytical design process. Also, deliberately search for handling problems, including the effects of design tolerances (parameter uncertainties) and failures. Identify the worst cases and any hidden weaknesses in the design, and fully explain any unexpected simulation results. A significant aspect of this recommendation is to use tasks which deliberately drive high pilot gain. This can be done through very stringent task performance requirements, or discrete gusts (not continuous turbulence that a pilot can ignore). It is critical that this part of the simulation should not be a check list of maneuvers that the pilot flies in a "relaxed" environment.

Relative to ACT2, evaluate the ability of the pilot to enter or re-enter the control loop, and obviously evaluate the pilot interface with the automatic functions. Show that there is no tendency for divergence between the automatic and manual control functions. Much of the preceding discussion has emphasized non-linearities. The simulation is where something like a non-linear stability problem may be found. In such a case, restricting the pilot's commands may help but is unlikely to provide a full solution. There still may be a stability problem provoked by an external disturbance, the effects of gusts should be examined.

Aeroservoelasticity and structural mode filter design

The primary function of the flight control laws is to provide the aircraft with good handling qualities by using feedback to the flying control surfaces. The airframe is not rigid and has many structural modes of vibration that may be excited by the control surface movements. The response of these lightly damped modes can be detected by the motion sensors and fed back to the control surfaces, with the potential for closed-loop instability at the structural mode frequencies. The application of modern high bandwidth flight control systems and advanced aerodynamic configurations has led to an increase in the levels of interaction between the airframe and its FCS. The aeroservoelasticity specialist has the task of defining a set of structural mode filters that provide sufficient attenuation of the structural mode content of motion feedback signals. The inclusion of ACT changes neither the requirement for these analyses nor the Best Practices in reference 1.

Design robustness and flight clearance

The certification or flight clearance process is essentially aimed at providing the evidence in order to certify that the aircraft is safe to fly. The qualification (validation) process is aimed at demonstrating that the design qualifies in meeting its design specification. If a satisfactory design has been achieved in accordance with the design requirements and guidelines, and the functionality is clearly defined, then these tasks should be relatively straightforward. However, the task is usually large and detailed, since there are very many cases which need to be assessed, covering a wide range of aircraft configurations and states, including parameter uncertainties, which have to be evaluated against a range of criteria to assess different aspects associated with safety and performance.

For ACT aspects, the piloted simulator should be used to complement the off-line analyses and in particular, to carry out more detailed investigations for regions of low stability or unusual handling. A critical area to investigate is the sensitivity to variations in certain basic model parameters. Some FCS design methods provide an estimate of 'robustness'. This should also be augmented with a more deterministic approach based on an assessment of model accuracy. Transients due to gusts, failures and mode changes should also be considered. Assessment of carefree handling functions needs to be very thorough, in order to demonstrate that the system is fully effective. This effort, however, will clear the system to enter a flight test program where the system will be finally validated

Developments during flight testing

A safe and well-planned program for the flight testing of the aircraft and its flight control system is essential. Flight testing of a flight control system usually involves some risk due to the uncertainties in the models used to establish the design, although this can be minimized by some of the best practices already covered. Once the flight test program has commenced, parameter identification is usually carried out, in order to validate the aircraft model. This leads to further flight clearances and increased confidence, enabling flight envelope expansion to continue in a safe and progressive manner.

For the higher levels of ACT implementation, special flight test procedures may be used and an example is discussed in Reference 1. Before giving a clearance for "carefree" handling flight tests, there were numerical simulations to show that the violations of defined boundaries stayed inside the allowed safety margin even for the worst case configurations. One of the main problems is that it is a multi-dimensional problem, where some parameters can augment each other. Moreover we have to look at a wide range of center of gravity, and during the prototype tests there are big tolerances on the aerodynamic modelling and the sensor system. Additional emergency precautions were done for one prototype. There were spin tests in the wind tunnel, a spin chute was fitted to that prototype, automatic start of the APU if the main engines stop due to spin, an extended emergency limit for the actuator rate, an emergency recovery mode of the flight controller with increased pilot authority, etc. Only this one prototype was allowed to fly in certain flight regions that were restricted for all other vehicles in the flight program.

At some point, the aircraft behavior may become significantly different from that predicted. The difference must be analyzed carefully, especially any trend with flight condition. There are many cases where differences were observed but thought to be small enough to allow flight testing to continue – until an incident occurred. At some point the behavior is deemed to be unacceptable, then control law changes will need to be introduced during the flight test program. Clearly, this needs to be done efficiently and safely in order to meet overall program timescales. Any differences in predicted behavior should always be investigated and fully explained.

Design considerations for PIO prevention

Although the application of the best practices in reference 1 will help to avoid pilot involved oscillations, it is considered that this topic warrants further comment, due to the problems it has caused the flight controls community in general. Much research has been carried out on this subject in recent years and the many results available can be quite daunting for a budding flight control engineer. To continue the earlier theme, the overall fuzzy logic is for the aircraft 'a) to do what the pilot wants to do when he wants it, b) to prevent any unintended responses, and c) only take command if the pilot tries to do something really stupid'. In terms of PIO, however, the overriding two principles are extremely simple. First, minimize time delays and phase lag, and second ensure that the pilot's command gain is neither too high nor too low.

The first of these is actually very, very straightforward. The mil spec approach, through the use of equivalent systems, requires that the equivalent system time delay be less than 100msec for Level 1 flying qualities. The required definition is in the frequency range of pilot control and, with the previously discussed requirement to include all non-linearities, will satisfy the requirements. Couple that with the criteria by John Gibson in reference 6, which extends design guidance through the complete frequency range, and time delay and phase lag will not contribute to flying quality deficiencies. There is one overriding caveat on that assertion, the models used in the design process must be accurate to within a threshold defined and considered in the design process.

The second aspect has caused problems in the past through the design being driven by simulation rather than analytical criteria. In a simulator, it can be taken as a given that a pilot will ask for more command gain, more response, more, more, more. As stated above, it is critical to search for problem areas. The test plan must include tasks that are more extreme than will be encountered in the expected mission use. It will not be sufficient to fly flight mission profiles or demonstration maneuvers in a straightforward, relaxed manner. A skilled pilot can often fly a deficient configuration until some event drives up his gain.

Management aspects

All good management practices are applicable to the development of the flight control system, and it is not intended here to write about what constitutes good management. However, there are some practices that are worth highlighting in order to emphasize their importance. The best overall management practice is to ensure that the detailed recommendations in Reference 1 are applied in any flight control system development.

First, a team must be formed to include representatives from each technical discipline and organization that have any contribution to the system.

A best practice is to plan carefully and don't underestimate the size of the job or the resources required. From collective experience of earlier projects, it must be assumed that there will be some surprises at some stage during the flight control system development, and some contingency planning might be necessary, including provision for software updates.

Lastly, the recommended management best practice relative to ACT is to ensure that it is integrated into the FCS design requirements as early as possible and follows the same disciplined design process.

Conclusions

Active Control Technology (ACT) can now be considered as part of the basic flight control requirements of a modern airplane. There is, however, a spectrum of detailed implementations from tailored flying qualities to automatic recovery functions. It is this author's prejudice that there are two absolutely critical points in any flight control design activity. First, define a complete set of design requirements, i.e. flying qualities criteria, up front. These should be based on the US Military Specifications augmented for the specific application with an understanding of the intent and expectations for each criterion. The design process is then to meet those criteria under all conditions, especially including predicted nonlinearities. Second, any deficiencies indicated by analysis, simulation or flight test must be supported analytically before any changes to the criteria are allowed. The control system must not be tuned in the simulator. If the specific requirements are defined early in the program, and then the design follows a disciplined process as indicated in Figure 1 and also expanded in Reference 1, then there is every reason to expect a successful system development.

Acknowledgement

The basic work that is reported in Reference 1 is the product of a working group comprised of:
Dr. David J. Moorhouse (Chairman), AFRL, USA
Mr. Wim de Boer, NLR, Netherlands
Mr. Chris Fielding, BAE, U.K.
Dr. Klaus-Uwe Hahn, DLR, Germany
Mr. Georg Hofinger, DASA, Germany
Dr. Leopoldo Verde, CIRA, Italy
Dr. Jean-Francois Magni, ONERA, France (part time).

In addition, there were contributions from many other people who are listed in the final report.

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Paper #25

Q by Bill Gubbels: Do you consider any other PIO criteria to be useful or is Gibson's criteria the only one you would say holds merit?

A. (D. Moorhouse): First, I would like to say that the best practice is to design for Level 1 flying qualities and not PIO avoidance. Gibson's is one criterion is a good way to do that. However, there are other valid PIO criteria. I have used Ralph Smith's criterion, although I do not agree that the feel system should be included in the formulation.

Q by Daniel Walker: What would it take to convince you that one design method for FCS was maybe better than another in a particular design problem? (vis-à-vis author's statement to the effect that the best design method is the one with which the designer was most comfortable) (sic.)

A. (D. Moorhouse): First, with the correct design criteria and good models, any method should arrive at the right answer but some more easily than others. I might also refer to a paper presented in 1994 that does discuss the best application of different methods for particular parts of the design problem. {Moorhouse and Citurs, "The Control System Design Methodology of the STOL and Maneuver Technology Demonstrator", AGARD Conference Proceedings, AGARD-CP-560}.